Orion Optical Navigation Performance and Testing

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Abstract: The Orion Optical Navigation System, which is designed to perform the navigation which will allow the crew to return safely to Earth in the event of a permanent loss of communications with the ground, has been matured through analysis and testing. This paper will detail the extensive tests and analysis that have gone into fleshing out the performance of the system in the face of numerous constraints placed on the optical navigation system.

The Orion Project has a requirement to return the crew safely to Earth in the event of a permanent loss of communications with the ground. In such an event, vehicle is designed with a capability to perform onboard navigation to provide a state estimate (position, velocity, attitude) for the guidance and targeting system to effect the maneuvers to achieve the desired landing site. To that end, Orion has been designed with an optical navigation system. This paper will briefly explore the design of the optical navigation system before detailing the testing and the anticipated performance of the autonomous onboard navigation system. In order to certify the optical navigation system, the first mission, Artemis I, which is uncrewed, will perform certification passes on the outbound leg of the mission.

The Artemis I Mission

The Artemis I mission, which is uncrewed, is intended to test the vehicle in preparation for the first crewed mission, Artemis II mission. Whereas the Artemis II mission is currently planned to be sent on a free-return trajectory around the Moon, the Artemis I mission will enter a Distant Retrograde Orbit around the Moon. As seen in Figure 1, during the approximate 25 day trajectory, after the Translunar Injection (TLI), the Artemis I mission will perform 2 powered lunar flybys of the Moon, the first called the Outbound Powered Flyby (OPF) and the second called the Return Powered Flyby (RPF). There are two additional deterministic maneuvers, the Distant Retrograde Insertion (DRI) and Distant Retrograde Departure (DRD). Along with the four deterministic maneuvers after TLI (OTC, DRI, DRD, and RTC), there are numerous correction maneuvers: four Outbound Trajectory Correction (OTC) maneuvers between TLI and OPF, two OTC maneuvers between OPF and DRI, 3 Orbit Maintenance (OM) maneuvers between DRI and DRD. Finally, there are 3 Return Trajectory Correction (RTC) maneuvers between DRD and RPF and 3 RTC maneuvers between RPF and Earth Entry Interface (EI). The times of these maneuvers are detailed in Table 1.

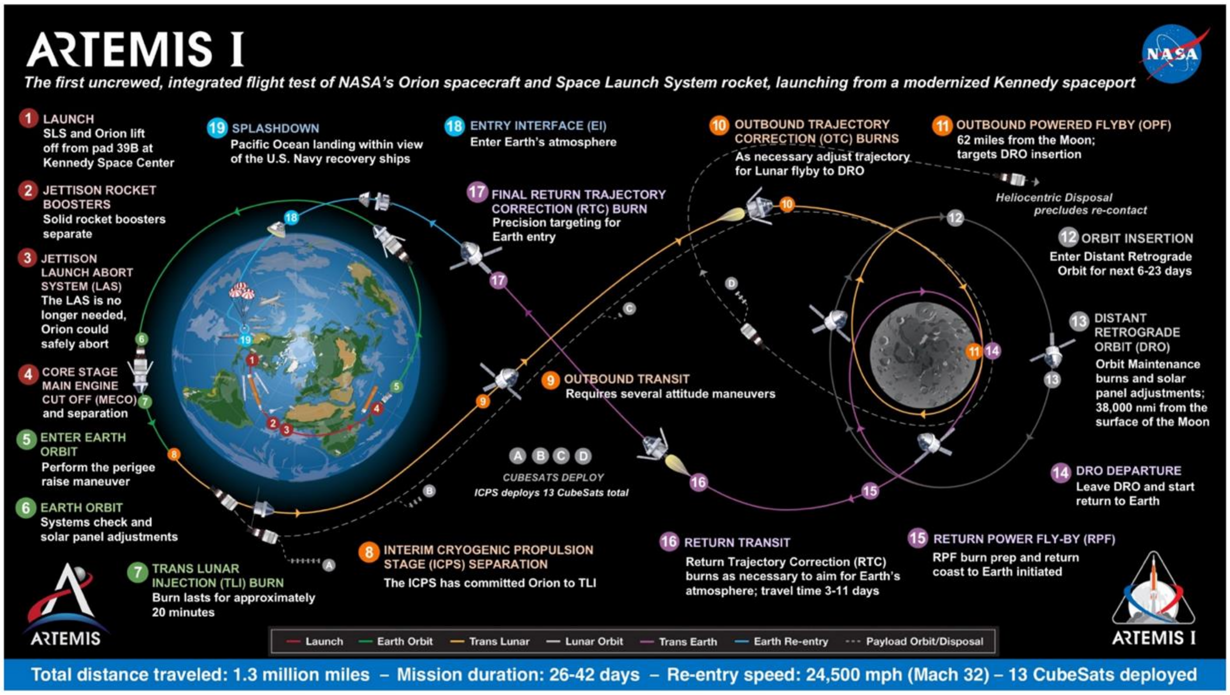


Figure 1: The Artemis I Mission

Of course, it is expected that the DSN will be the primary navigation source during the outbound leg of the mission, thereby providing an accurate estimate of the state of the vehicle, which will allow for an evaluation and certification of the onboard optical navigation system.

Of all the driving requirements, the most important and significant are that of achieving an EI delivery state, which would assure a safe return of the crew to Earth.

The Optical Navigation Concept of Operations

There are several constraints imposed on the ability to navigate the Orion vehicle, chief amongst them is the requirement to orient the vehicle with a tail-to-sun attitude because of thermal considerations. This places constraints on the frequency and location of the optical navigation passes. In particular, this places a rather significant constraint on the optical navigation passes prior to the final maneuver (RTC-6). The optical navigation concept of operations is depicted in Figure 2.

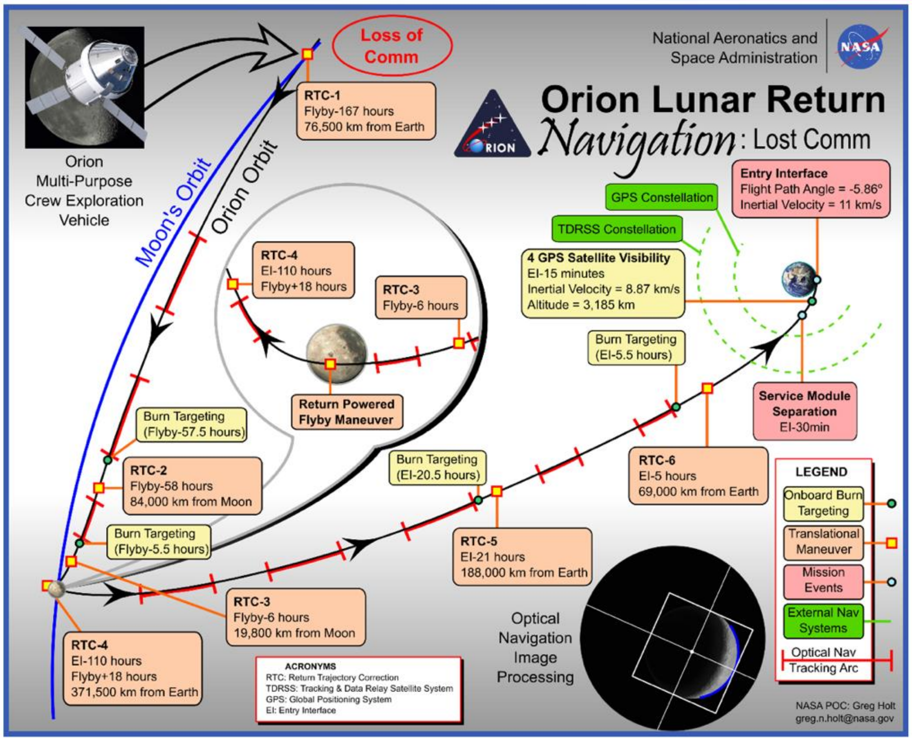


Figure 2: The Optical Navigation Concept of Operations

The optical navigation camera is mounted aft of the crew cabin, on the Crew Module Adapter (CMA) on an optical bench, mounted between the two star trackers. The optical navigation camera is a Pixel link camera with a 1 Megapixel Focal Plane Array and a 35.1 mm lens along with a lens baffle to reduce/eliminate stray light.

During the planning of the operations of Artemis I, it was anticipated that the planetary target during the optical navigation passes would be the closest body, i.e. when the vehicle was closer to the Moon, the optical navigation camera would be pointed at the Moon and when the vehicle was closer to the Earth, the Earth would be the target body. This imposed constraints on the trajectory which were thought to be too stringent, namely the launch opportunities to allow for a illumination of the Earth's limb with a specified Sun exclusion angle during optical navigation passes.

In the rest of the paper, we will detail the analysis that we undertook to remove many of these restrictions which opened up more launch opportunities. In particular, the question which was asked whether looking at the Moon on the final four passes (which were nominally planned to be Earth passes) would allow the EI requirements to be met. This analysis comprised four elements: an analysis of the sensitive factors on launch availability, a detailed study of the Sun exclusion angle, investigation of the accuracy of the optical navigation measurement of the Moon at Earth distances using an International Space Station (ISS) observations of the Moon in a so-called Detailed Test Objective (DTO), and a covariance analysis of the EI delivery accuracy.

The Launch Availability Analysis

With respect to launch availability the three driving requirements were: landing at the desired water landing point (in the vicinity of San Diego) in daylight, performing outbound optical navigation certification passes with the Earth as the target early in the trajectory and the Moon as the target later in the translunar trajectory, and the Sun Exclusion angle for optical navigation passes during the final four optical navigation passes. With these constraints in effect, the number of launch opportunities over a one-year period was 86 days.

However, if on the return leg, the target body is allowed to be flexible, the number of launch opportunities increases to 97 days.

Finally, if the targets and locations of the outbound certification passes and the return target body is allowed to be flexible, releasing the optical navigation constraints on launch availability, the number of available days to launch increases to 111 days, an increase of 25 days.

These launch availability opportunities are assuming a Sun exclusion angle of 19 degrees.

The ISS Optical Navigation Experiment (DTO)

Whereas a great deal of testing of the optical navigation camera and its associated image processing software was done on the ground using synthetic imagery and a measurement error model was developed from these numerous images, it was desired to anchor this measurement error model with real imagery taken in space. The ISS provided an ideal platform to perform these tests. Three sets of observation sessions were performed, from the ISS Cupula windows, using the COTS equivalent to the Orion optical navigation camera – a PixeLink PL-D725M (a 5.3 Megapixel monochrome) camera with a Schneider 35 mm lens. Table 2 contains a description of the optical navigation sessions.

Day	Moon Phase	Day/Night	Crew
Aug 27, 2018 (day 239)	Waning gibbous	Day	Drew Feustel
Jan 29, 2019 (day 29)	Waning crescent	Night	David Saint-Jacques
Mar 31, 2019 (day 90)	Thin waning crescent	Night	David Saint-Jacques and Ann McClain

Figure 3 contains an example of an image taken on the March 31, 2019 session which is a thin waning crescent.

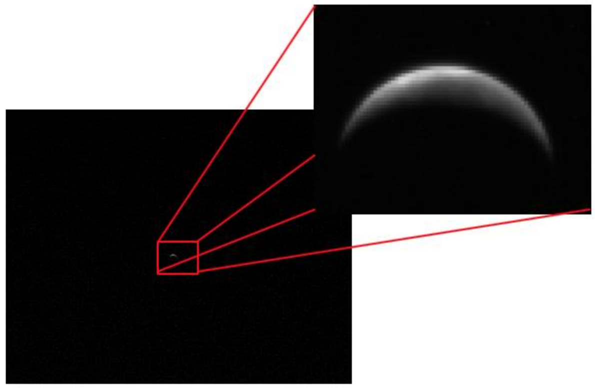


Figure 3*:* **Sample Image from the March 31, 2019 ISS DTO Session**

Figure 4 is an example of an image taken on the January 29, 2019 session during which the Moon was a waning crescent.

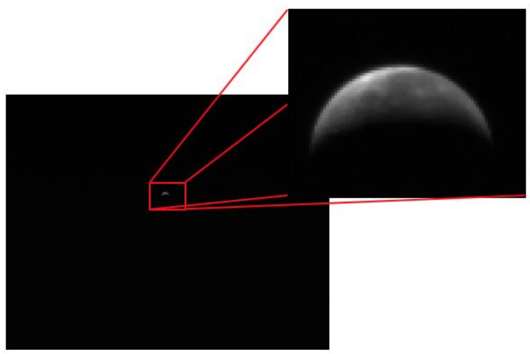


Figure 4*: Sampl***e Image from the January 7, 2019 ISS DTO Session**

These images were post-processed on the ground. The results of both sessions are shown in Figures and . They show that whereas there is a bias in the range measurement error, the errors are still within the 3-sigma bounds predicted by the model at Earth distances.

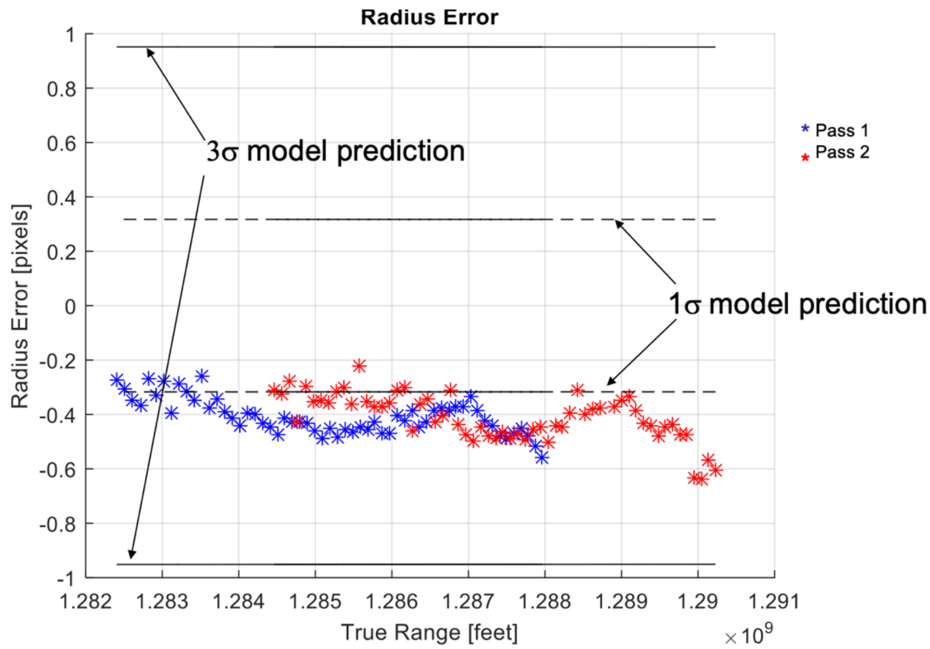


Figure 5: Radius Measurement Error from ISS DTOs

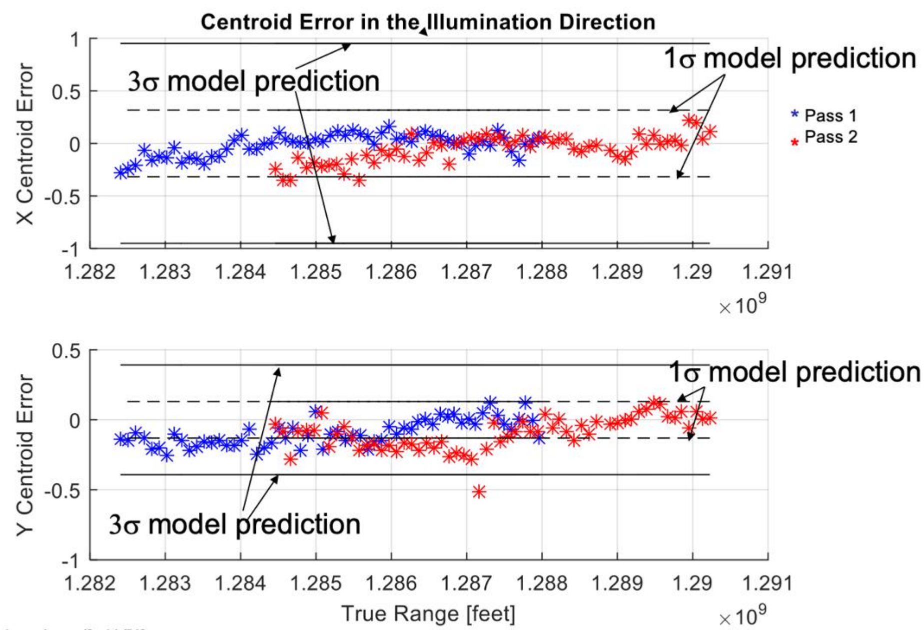


Figure 6: X and Y Centroid Errors from ISS DTOs

The Analysis of the Sun Exclusion Angle (SEA)

The Orion optical navigation system has undergone extensive tests in the optical laboratory at JSC called the Electro-Optics Lab (EOL). This objective of this set of tests was to evaluate the minimum SEA that would produce images without any optical artifacts. Whereas, the optical navigation camera does provide a measure of protection against bright bodies, it was desired to investigate in detail what this 'optimal' SEA is. The test setup is shown in Figures 7 and 8.

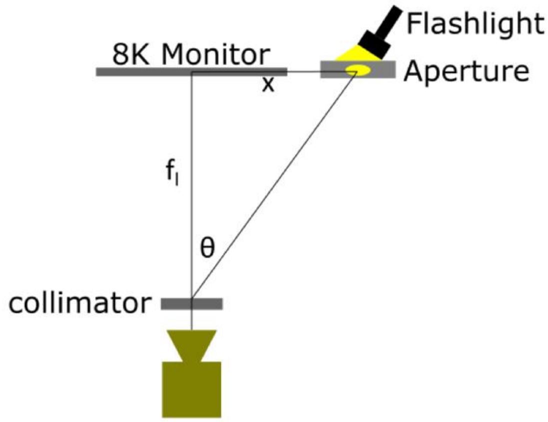
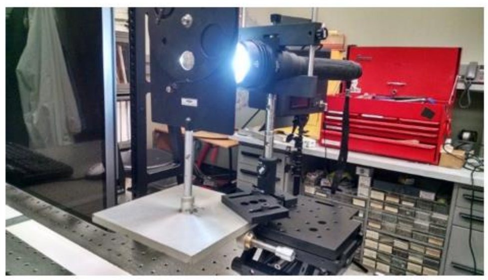
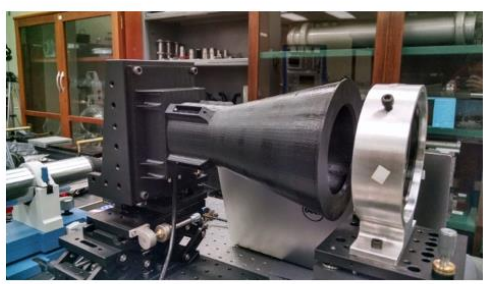


Figure 7: The Geometry of the SEA Test



Sun Simulator: Light source behind circular aperture that translates to 0.6^o in diameter



3D Printed Baffle Mounted w/ Camera in OCILOT

Figure 8: The OCILOT SEA Test

The results of the tests are depicted in Figure 9 which shows that the optimal Sun Exclusion Angle is 19 degrees.

Figure 9: **Variation of the Sun Exclusion Angle**

Linear Covariance Analysis of the Optical Navigation System

An extensive Linear Covariance (LinCov) analysis was performed on the optical navigation system. LinCov is a powerful navigation analysis tool that gives comparable statistical performance of Monte Carlo analysis but in a single run. It assumes a nominal trajectory and it analyses the behavior of the navigation errors and trajectory dispersions about the nominal trajectory. Therefore, it is possible to not only analyze the navigation performance but also the delivery errors and the DV performance. Considering the length of the Artemis I trajectory, LinCov has been used as a stand-in for extensive Monte Carlo analysis; as well, it provides a platform for sensitivity analysis.

To that end, the optical navigation system was analyzed with an eye toward determining the delivery errors as a function of the planetary body being tracked on the final four maneuvers. This analysis also included the effect of missed optical navigation passes. In particular, when the Moon was tracked in one or more of the final optical navigation passes, there was a marked improvement n delivery accuracy. In order to see this, Figure 10 contains the EI delivery performance for the nominal case (when the Earth was tracked during the final four passes).

A few words need to be said about these EI delivery plots. The parameters of primary importance are (in order) the flight path angle, the downrange error, the velocity magnitude, and the out-of-plane errors. These plots aim to capture not only the errors in each of those components but the correlation between these components, expressed in terms of error ellipses. In addition to the actual delivery errors (in red), the requirements, specified by the Entry team, are plotted in black.

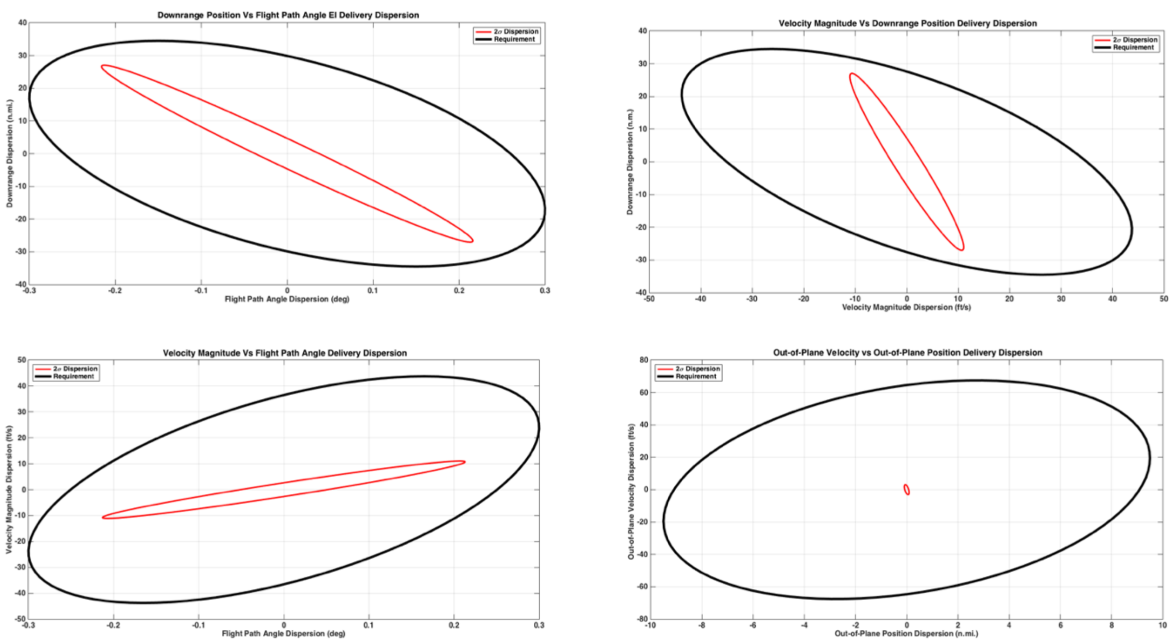


Figure 10: EI Delivery Performance with Nominal Pass Schedule (final 4 Earth Passes)

Thus, Figure 10 shows that all the requirements are satisfied for the `nominal' performance, albeit with very little margin. However, when the Moon was observed for all of the final passes, instead of the Earth, the performance in the in-plane errors (downrange, flight-path-angle, velocity) improve substantially while the out-of-lane performance degrades. This is seen in Figure 11. Thus, looking at the Moon on the final 4 passes improves EI delivery errors.

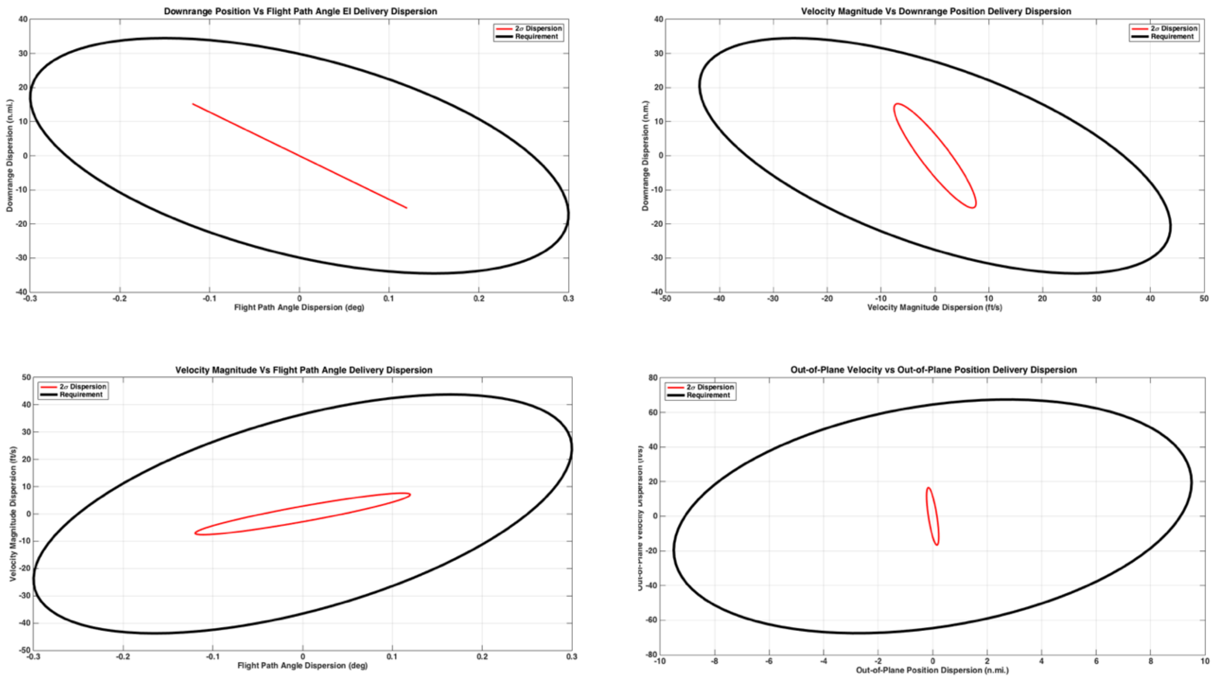


Figure 11: EI Delivery Performance with All Moon Passes

Conclusions

This paper has presented the maturity and responsiveness of the Orion Optical Navigation system in the presence of operational constraints, particularly thermal and Sun exclusion angle constraints. The tests that were performed in order to validate the performance were detailed.